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Characterization and comparison of biomass produced from various sources: Suggestions for selection of pretreatment technologies in biomass-to-energy

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HIGHLIGHTS

- ▶ Biomass with higher volatile matter content has a higher carbon conversion rate.
- ▶ Applying the suitable pretreatment techniques that will enhance the bioenergy yield.
- ▶ The ratio of H_2O/fixed carbon is a critical factor for enhancing the energy conversion.

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ABSTRACT

This study investigated the characteristics of 26 varieties of biomass produced from forestry, agriculture, municipality, and industry in Taiwan to test their applicability in thermal conversion technologies and evaluation of enhanced energy efficiency. Understanding the reactivity of the tested biomass, the cluster analysis was also used in this research to classify into characteristics groups of biomass. This research also evaluated the feasibility of energy application of tested biomass by comparing it to the physicochemical properties of various coals used in Taiwan's power plants. The experimental results indicated that the volatile matter content of the all tested biomass was 60% and above. It can be concluded that the higher carbon conversion rate will occur in the thermal conversion process of all tested biomass. Based on the results of lower heating value (LHV) of MSW and non-hazardous industrial sludge, the LHV was lower than other tested biomass that was between 1000 and 1800 kcal/kg. This is due to the higher moisture content of MSW and sludge that resulted in the lower LHV. Besides, the LHV of other tested biomass and their derived fuels was similar to the tested coal. However, the energy densities of woody and agricultural waste were smaller than that of the coal because the bulky densities of woody and agricultural wastes were low. That is, the energy utilization efficiency of woody and agricultural waste was relatively low. To improve the energy density of tested biomass, appropriate pre-treatment technologies, such as shredding, pelletizing or torrefied technologies can be applied, that will enhance the energy utilization efficiency of all tested biomass.

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1. Introduction

This is particularly true of bio-energy development in which the relative roles of the Taiwanese government and private industry, as well as the substantive content of the programs, are of continuous concern. Based on the Taiwan's Renewable Energy Development Act, the bio-energy is defined as energy which is produced directly or indirectly from agriculture and forestry plants, biogas and domestic organic waste, etc. Accordingly, biomass refers to biological organic materials, such as wood and forestry waste, crops, agricultural waste, livestock waste, municipal solid waste (MSW), sewage or wastewater sludge and industrial organic waste, etc. According to the results of static data from Taiwan's Bureau of Energy, Ministry of Economic Affairs, the installation capacity of bio-energy was approximately 814.5 MW. The most bio-energy was produced from MSW which the installation capacity was approximately 622.5 MW. In 2020, the installation capacity of bio-energy could be expected to increase to 1030 MW. It is necessary to estimate the potential of existing biomass. Approximately 225 million tons of biomass is produced each year. The biomass could be used as the energy feedstock including MSW, industrial non-hazardous organic waste, wood, agricultural waste, and organic sludge, etc.

The characteristics of biomass are of a great variety and come from different sources. To establish the database of the physical and chemical properties of biomass, it could help to understand how the fundamental knowledge on the composition and properties may be implemented for the most advanced energy utilization

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and environmental safe of biomass. Meanwhile, the variations of physical and chemical characteristics of various biomass, including moisture content, fixed carbon, volatile matter and ash content, ultimate analysis, chemical composition and heating value, etc., may cause design and operational problems in thermal conversion system [1–3]. Generally, synthesis gas was produced and enhanced by the water gas shift reaction in gasification. On the contrary, high moisture content will decrease the reaction temperature to cause the hydrocarbon compounds to partially crack in the pyrolysis zone because the heat absorbed by evaporation of water during the thermal conversion process [4–7]. The particle size of the tested biomass was also a critical parameter for evaluating the thermal reaction rate and energy yield. In general, a smaller particle size of the tested biomass can accelerate the reaction rate and enhance the energy yield efficiency [8–10].

The heating value of biomass is an important parameter for describing the energy content and design of the thermal conversion system [11,12]. Literatures information is available on the combined chemical composition and heating value of biomass. It was noted that its composition and heating value are significantly different from that of coal. Besides, the variations between the heating value and chemical composition of biomass were also found to be greater than that of coal. Therefore, understanding of the characteristics of biomass will help in the blending of different biomass types and in designing the optimum thermal conversion system. To develop the empirical equations for the prediction of the heating value of biomass, mathematical models have been published to relate the heating value of biomass to the results of ultimate or proximate analysis [11,13].

Energy-to-biomass can be converted by thermo-chemical and bio-chemical processes. Generally speaking, thermo-chemical technologies have higher conversion efficiency than that of bio-chemical technologies. At the same time, thermo-chemical technologies have good destructive ability of organic compounds and require shorter reaction time. Therefore, thermo-chemical technology has been extensively applied for energy conversion in many countries. The major thermo-chemical technologies are including combustion, pyrolysis, gasification, liquefaction, and torrefaction [14,15]. In recent years, carbon capture and storage (CCS) has become an important environmental issue. Many researches focused on the enhancement of energy utilization and carbon capture efficiency in biomass-to-energy processes. Oxyfuel combustion enables CCS by burning fuels with a combination of pure oxygen and recycled flue gas instead of air. This is because fuel is burnt in pure oxygen, the flame temperature is excessively high, and so some CO_2-rich flue gas would be recycled to the combustor to make the flame similar to that in a normal air-blown combustor [16]. Enriched air mixture contains a mixture of carbon dioxide and oxygen that was also widely applied to act as the gasification medium and to increase the heating value of synthesis gas [17]. Torrefaction is one of thermo-chemical technologies of biomass at a relatively lower temperature in absence of oxygen. It is necessary to remove oxygen of biomass before gasification or other thermo-chemical technologies due to the high oxygen content of the biomass. The results of previous study indicated that decrease O/C ratio in biomass from torrefaction can result in heating value of biomass increasing [15]. Besides, some researchers attempted to apply the hydrothermal technology on different kinds of biomass to produce powder-like solid fuels [18]. That is, hydrothermally treated biomass is proved to be able to co-firing with coal at a controlled blending ratio and to act as an alternative fuel.

With regard to the biomass converted to bio-oil and/or bio-gas by pyrolysis and/or gasification, most previous researches focused on upgrading of the bio-oil, improving of synthesis gas quality, and enhancing of energy yield efficiency during biomass gasification by various catalysts. To achieve above target, the mineral, metal-based, and precious metals were widely used as the catalysts. The energy production, purchasing cost, availability, and the rate should be considered as factors to choose a catalyst. With the benefit of mineral catalysts, many groups took materials from minerals like dolomite, CaO, olivine, and iron ore as the catalyst to study the energy production and separate the CO_2 from syngas in biomass-to-energy [19–26]. However, little information has established relationships between the characteristics of biomass and energy yield in thermal conversion. Therefore, it is essential to obtain a better understanding of the physical and chemical properties of various types of biomass for selection in thermal conversion technologies and evaluation of enhanced energy efficiency. The objectives of this research were to (1) analyze and compare the composition characterization of various types of biomass; (2) investigate the effects of energy yield efficiency from various types of biomass; (3) suggest the feasibility of pre-treatment techniques for selecting prior to the subsequent thermal conversion process.

2. Materials and methods

2.1. Materials

The representative biomass samples were collected from various sources, such as forestry, agriculture, municipality, and industry, that were to be treated or disposed of in Taiwan. In this research, we chose 26 varieties of common biomass including eight varieties of grass and agricultural biomass samples, three varieties of woody biomass samples, 10 varieties of non-hazardous industrial biomass wastes and five varieties of coal samples.

2.2. Analysis methods

The properties of the tested biomass samples consists of proximate analysis (including the fixed carbon content), ultimate analysis, and energy content. To understand the feasibility of biomass used as an alternative fuel, the characteristics of reactivity in the tested biomass samples were classified by cluster analysis method. In addition, energy density was also used to assess the energy yield efficiency in thermal conversion. The cluster analysis method was used in this research to separate different characteristics groups so that it could illustrate the relationship between the reactivity and energy yield of tested biomass samples. The characteristics indexes used in this research, including the energy content (heating value), hydrogen–carbon ratio, oxygen-carbon ratio, moisture-fixed carbon ratio, and energy density, were used to classify the groups for selection of pretreatment techniques.

2.3. Characterization of tested biomass

The moisture content of the test samples was determined by heating for 24 h at 105 C. The volatiles, fixed carbon, and ash fraction of the samples were determined in triplicate under the regulation tested procedures (National Institute of Environmental Analysis, NIEA R203 and R205) of the Taiwan Environmental Protection Administration (EPA). The ultimate analysis on the combustible in the tested biomass was analyzed using an elemental analyzer (Elementar Vario E III). The energy content of tested biomass was determined, using a laboratory bomb calorimeter (Parr 1341 calorimeter). All test data was repeated three times to ensure the accuracy and reproducibility. The energy density was defined the energy content stored in biomass per unit volume (kcal/m^3), calculated as:

$$\mathrm{ED} = \mathrm{LHV}\ (\mathrm{kcal/kg}) \times \mathrm{Bulk\ density}\ (\mathrm{kg/m^3}) \tag{1}$$

Before each cellulose and lignin experiment, the tested samples were mechanically shredded and sieved to a particle size of approximately 0.25–0.425 mm each. The tested biomass powders are extracted for 6 h in ethanol–benzene of 1:2 (v/v of biomass to the solvent) in a Soxhlet apparatus. Then, the chemical analyses in the residue after the extraction are conducted. The residue was dried and extracted by solution of acetic acid and sodium chlorite that it operated at 70–80 °C in a water bath for 4 h. Samples are extensively washed until the pH of filtrate is neutral. The samples are dried and weighted for determining their cellulose contents. With regard to the lignin content analysis the residue was produced from Soxhlet apparatus and then dried and extracted by 72% sulfuric acid at room temperature for 2 h, followed by hydrolysis in 3% sulfuric acid at 100 °C for 4 h. The remaining residues are filtered and dried for determining their acid-insoluble lignin content. The aqua is an acid-soluble lignin content that is filtered through 0.45-μm pore size filter and measured by a UV–spectrophotometer (SHIMADEZU UV-1700) at a wavelength of 205 nm (Chinese National Standard, CNS 12108).

3. Results and discussion

3.1. Proximate composition of biomass and comparisons with coals

The moisture content, volatile matter, fixed carbon, and ash content are important factors of the biomass thermal conversion system and require a more detailed understanding for comparison with coal. The moisture content in tested various types of biomass varied significantly, and ranged between 4% and 72% (as shown in Table 1). This is due to the fact that specific biomass, such as MSW, sludge, and some agricultural waste (e.g. mushroom waste, fresh Chinese Pennisetum), contains higher moisture content at as received basis. The moisture content in woody biomass and waste derived fuel is commonly in the more narrow range from 1% to 20%. It seems to have similar moisture content to the coals. Generally speaking, the lower moisture content in biomass will have much higher heating value for producing energy yield in the thermal conversion system. Therefore, the chosen biomasses used in this research are roughly complied with the energy application.

The volatile matter and fixed carbon content in biomass are good parameters for evaluating the volatility and ignitability of biomass. The analysis results indicated that volatile matter and fixed carbon content of woody biomass, grass and agricultural biomass, and fuel derived from non-hazardous industrial waste were approximately between 60%-80% and between 10%-20%, respectively (as shown in Table 1). The volatile matter/fixed carbon ratios are on the order of 3.2–16.45. Especially for the refuse-derived-fuel (MSW-RDF-5), it has a higher volatile matter/fixed carbon ratio resulting in its flammability during the thermal conversion process. However, the volatile matter/fixed carbon ratios of coals were ranged between 0.09 and 0.88. Typical volatile matter/fixed carbon ratios for coals are normally in the interval of 0.6–2.4 [27]. This means that the coals generally exhibit less volatility in the thermal conversion process. In addition, high volatile matter content has a lower ignition temperature and high ignition stability to produce synthesis gas during the biomass gasification process. With respect to the higher fixed carbon content in biomass it is important to note that the thermal reaction required a longer time to produce synthesis gas by various catalysts.

Fig. 1 shows the co-relationships among the volatile matter, fixed carbon and ash content in various biomasses. It can clearly illustrate that the differentiations between the tested biomass and coals. According to the results of mean proximate composition, the similarities among various tested biomass are significant and there is a relatively closer position of woody biomass to agricultural waste than coals. Similar observations were also published earlier [27].

The ash content of various kinds of biomass used in this research ranged between 1% and 15%, respectively. Meanwhile, significant differences appear between the agricultural waste and the woody biomass, particularly the ash content of the agricultural waste was higher than that of the woody biomass. On the other hand, agglomeration and erosion problems could occur in a gasification system due to the biomass ash containing high alkali content with the potential of lowering the ash fusion temperature. In summary, the chosen biomass samples were highly reactive combustible solid bio-fuels resulting in higher synthesis gas production and energy yield during thermal conversion process.

3.2. Chemical composition of biomass and comparison with coals

Table 1 also indicated that carbon, hydrogen, oxygen, nitrogen, sulfur, and chlorine content are present in tested biomass. The main constituents of biomass were carbon, hydrogen, and oxygen, respectively. The carbon content of all tested biomass varied in the range of 44–78% (dry ash-free, daf). Normally, the carbon content in biofuels derived from wastes is approximately 50–60% which means it has a higher carbon content than that of other tested biomass. With respect to carbon content it is important to distinguish between biomass and coal. The carbon content in the coal was approximately 70–90%, respectively. The hydrogen content in all tested biomass varied widely, ranging from 5% to 17%. In general, extremely high hydrogen content is characteristic of biofuel derived from plastic waste (HP-RDF-5). The hydrogen content in the coal was commonly lower than that of biomass. The other main constituent in the biomass was oxygen element. The oxygen content in typical woody biomass and agricultural waste were approximately 40% and above. However, the hydrogen content in coals only ranged between 3% and 6%. Based on the results of the ultimate analysis, the chemical composition of the organic matter in selected biomass is characterized. Empirical chemical formulas for the selected biomass are presented in Table 2.

To further consider the reactivity of tested biomass, the hydrogen–carbon molar ratio (referred as H/C) and oxygen-carbon molar ratio (referred as O/C) were important parameters for evaluating the characteristics of bio-energy application. Experimental results indicated that the H/C and O/C ratio in tested biomass samples have a higher value than that of coal. It is noted that the biomass generally exhibits more volatility and energy yield in a thermal conversion system. Fig. 2 shows a ternary phase diagram of the molecular ratios of carbon, hydrogen, and oxygen for various biomass samples in order to summarize the specific groups for selection in a thermal conversion system. Accordingly, the tested woody biomass, grass and agricultural waste are suitable for application in gasification or pyrolysis systems as their hydrogen content was higher than that of coal.

The sulfur and chlorine content in the tested biomass varied in the interval of 0.1–6% and 0.02–2.08%, respectively. Various RDF-5 samples are manufactured from different waste and/or biomass sources and have comparatively variable characteristics. The chlorine content of RDF-5 was actually high (as shown in Table 1). It was noted that various RDF-5 samples have higher sulfur content than woody biomass, agricultural waste, and coal. Therefore, the HCl and H_2S emission will be taken into consideration during the energy conversion process of various RDF-5 samples in the future.

3.3. Energy content of biomass and comparison with coals

The energy content of biomass (also referred to as heating value) is essential for evaluating its potential as fuel in the thermal conversion system. In general, the heat is released when a known quantity of biomass is burned under specific conditions. The energy content of tested biomass samples chosen in this research

Table 1
Characteristics of various types of biomass and coal.

Biomass group	Proximate analysis (%)					Ultimate analysis (daf, %)						LHV (Kcal/kg)	Bulk density (kg/m^3)	Energy density (Mcal/m^3)
	Moisture	Ash	Combustible			C	H	N	O	S	Cl			
			FC	VM	Total									
Woody biomass														
Longan trimmings	14.05 ± 0.11	3.64 ± 0.10	19.60	62.71 ± 0.37	82.31	51.97 ± 0.23	4.97 ± 0.10	1.07 ± 0.05	41.71	0.21 ± 0.02	0.07 ± 0.02	3505	600	2103
Sawdust*	11.30 ± 2.81	0.68 ± 0.11	16.03	71.99 ± 1.75	88.02	49.88 ± 0.62	6.87 ± 0.68	0.94 ± 1.03	41.90	0.35 ± 0.09	0.06 ± 0.02	3778	450	1700
Willow	11.86 ± 0.15	0.59 ± 0.06	13.86	73.69 ± 0.38	87.55	49.67 ± 0.27	6.70 ± 0.23	0.26 ± 0.03	43.15	0.14 ± 0.01	0.08 ± 0.02	3809	600	2285
Grass and agricultural biomass														
Bamboo trimmings	11.11 ± 0.02	3.14 ± 0.11	15.56	70.19 ± 1.14	85.75	51.82 ± 0.09	5.47 ± 0.09	0.88 ± 0.06	41.48	0.23 ± 0.05	0.12 ± 0.02	3633	250	908
Bamboo's chopsticks	9.37 ± 1.01	1.20 ± 0.28	13.47	75.96 ± 5.71	89.43	46.83 ± 0.96	5.00 ± 0.60	0.16 ± 0.02	47.50	0.39 ± 0.07	0.12 ± 0.03	3432	250	858
Rice husks	9.68 ± 0.27	11.96 ± 0.23	15.93	62.43 ± 0.53	78.36	48.60 ± 1.58	6.70 ± 0.31	0.38 ± 0.04	43.66	0.43 ± 0.11	0.23 ± 0.01	3558	175	623
Rice straw	10.71 ± 0.66	9.46 ± 0.81	15.61	64.22 ± 0.55	79.83	46.21 ± 0.96	7.24 ± 0.74	1.89 ± 1.01	43.48	0.64 ± 0.26	0.54 ± 0.09	3195	120	383
Chinese Pennisetum (dry)	4.56 ± 0.09	3.50 ± 0.14	16.99	74.95 ± 1.28	91.94	46.03 ± 0.11	7.76 ± 0.23	0.61 ± 0.04	44.91	0.47 ± 0.05	0.23 ± 0.01	3878	200	776
Chinese Pennisetum (fresh)	72.35 ± 0.50	1.36 ± 0.11	–	–	26.29	46.33 ± 0.23	6.05 ± 0.11	2.13 ± 0.15	44.73	0.53 ± 0.04	0.23 ± 0.04	680	200	136
Mushroom waste	53.29 ± 0.16	3.23 ± 0.04	10.12	33.36 ± 0.23	43.49	51.87 ± 0.37	4.99 ± 0.34	1.38 ± 0.14	41.02	0.51 ± 0.05	0.23 ± 0.05	1689	200	338
Edible grass-stem (Jiao bai sun)	12.74 ± 0.18	10.51 ± 0.17	10.06	66.69 ± 2.19	76.95	47.23 ± 0.16	6.36 ± 0.20	1.62 ± 0.04	43.99	0.57 ± 0.03	0.23 ± 0.01	2810	200	562
Banana trimmings	11.74 ± 0.27	6.34 ± 0.04	19.46	62.46 ± 9.58	81.92	50.42 ± 0.31	6.29 ± 0.07	1.14 ± 0.04	41.67	0.33 ± 0.04	0.15 ± 0.01	3374	200	675
Industrial biomass wastes														
Active sludge	56.78 ± 1.28	7.63 ± 0.05	5.60	29.99 ± 0.31	35.59	48.83 ± 0.20	5.62 ± 0.14	0.93 ± 0.03	43.80	0.67 ± 0.06	0.14 ± 0.00	1051	260	273
MSW	53.23 ± 1.95	6.43 ± 2.09	–	–	40.34	54.91 ± 3.88	8.48 ± 1.09	1.12 ± 0.47	34.38	0.85 ± 0.40	0.27 ± 0.12	1756	144	253
MSW-RDF-5	21.50 ± 0.75	8.52 ± 0.80	4.01	65.97 ± 0.43	69.98	51.75 ± 2.22	6.42 ± 0.29	0.83 ± 0.09	40.53	0.24 ± 0.01	0.23 ± 0.06	3449	240	828
B-RDF-5	18.97 ± 0.08	9.43 ± 0.88	10.59	61.01 ± 0.52	71.60	48.95 ± 1.75	5.71 ± 0.18	1.45 ± 0.20	43.18	0.36 ± 0.06	0.34 ± 0.03	3205	370	1186
RDF-5	8.05 ± 2.75	16.27 ± 3.24	–	–	75.68	44.00 ± 5.30	6.82 ± 1.41	0.81 ± 0.57	47.15	0.66 ± 0.40	0.57 ± 0.40	3933	500	1967
P-RDF-5	3.79 ± 0.49	7.76 ± 0.88	9.86	78.59 ± 1.62	88.45	66.90 ± 5.23	11.00 ± 0.86	0.26 ± 0.11	21.20	0.26 ± 0.01	0.38 ± 0.01	5992	500	2996
HP-RDF-5	0.68 ± 0.12	3.31 ± 1.12	–	–	96.01	78.03 ± 2.47	17.01 ± 2.83	0.03 ± 0.01	3.12	0.27 ± 0.10	1.53 ± 1.16	8574	400	3430
IP-RDF-5	10.98 ± 11.21	14.13 ± 11.52	–	–	74.89	54.36 ± 14.0	8.57 ± 1.75	0.79 ± 0.72	33.44	1.01 ± 0.31	1.83 ± 3.22	4647	400	1859
R-RDF-5	6.97 ± 0.43	7.43 ± 0.71	–	–	85.60	49.35 ± 0.23	6.53 ± 0.30	0.01 ± 0.00	43.39	0.37 ± 0.00	0.35 ± 0.04	4326	500	2163
W-RDF-5	10.02 ± 3.08	10.73 ± 2.69	20.18	59.07 ± 0.48	79.25	49.32 ± 10.09	7.07 ± 1.12	2.13 ± 0.79	37.58	2.60 ± 3.09	1.30 ± 0.83	3507	430	1508
Coal														
Anthracite coal	2.36 ± 0.08	8.41 ± 1.97	82.20	7.03 ± 0.23	89.23	92.23 ± 3.35	3.61 ± 0.25	1.59 ± 0.07	1.82	0.66 ± 0.07	0.09 ± 0.01	6782	850	5765
Bituminous coal	8.71 ± 0.02	4.87 ± 0.45	56.47	29.95 ± 0.21	86.42	80.42 ± 1.24	4.66 ± 0.32	1.02 ± 0.03	13.52	0.34 ± 0.02	0.05 ± 0.00	5683	850	4831
Subbituminous coal	5.57 ± 0.05	12.55 ± 0.34	55.33	26.55 ± 0.29	81.88	76.34 ± 0.20	4.37 ± 0.35	1.86 ± 0.01	16.87	0.50 ± 0.02	0.06 ± 0.00	5810	850	4939
Lignite coal	2.70 ± 0.04	44.73 ± 0.83	28.05	24.52 ± 0.14	52.57	66.50 ± 4.55	4.45 ± 0.25	1.26 ± 0.13	17.75	9.99 ± 1.27	0.06 ± 0.00	2954	850	2511
Envirocoal	12.74 ± 0.04	6.46 ± 0.68	43.00	37.80 ± 0.18	80.80	68.04 ± 1.25	5.21 ± 0.14	1.46 ± 0.04	24.73	0.52 ± 0.07	0.04 ± 0.00	4831	850	4106

Notes: not available; VM: Volatile matter; FC: Fixed carbon; daf: Dry, ash-free basis; MSW: municipal solid waste; MSW-RDF5: municipal solid waste-derived fuel; B-RDF-5: biomass-derived fuel; RDF-5: refuse-derived fuel; P-RDF-5: paper-derived fuel; HP-RDF-5: household-plastic-derived fuel; IP-RDF-5: industrial plastic-derived fuel; R-RDF-5: rubber-derived fuel; W-RDF-5: wood-derived fuel.

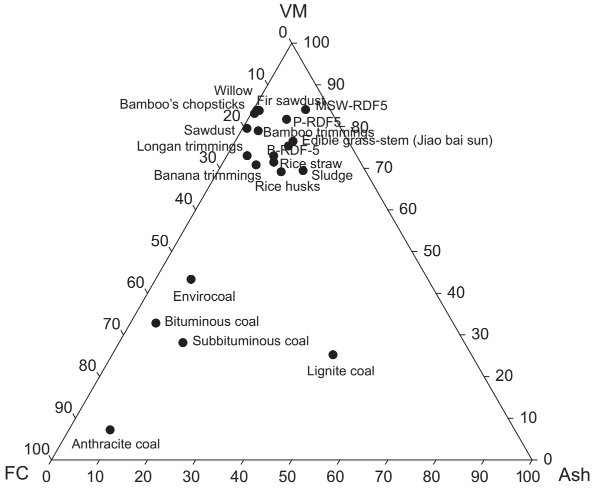

Fig. 1. Ternary phase diagram of the contents of volatile matter, fixed carbon and ash content in various types of biomass.

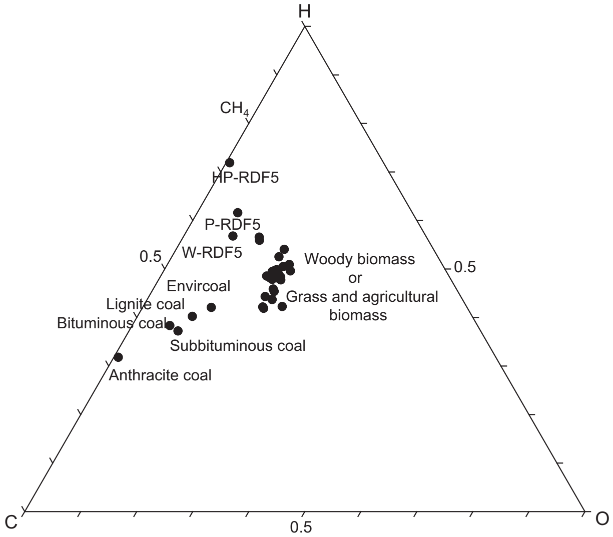

Fig. 2. Ternary phase diagram of the mole ratios of carbon, hydrogen and oxygen in various types of biomass.

can vary between 680 kcal/kg and 8574 kcal/kg (as shown in Table 1). This variability in tested biomass samples is due to changes in their type, source, and composition. Table 1 indicated that the household-plastic-refuse-derived fuel (HP-RDF-5) sample typically has higher energy content (approximately is 8000 kcal/kg and above). Different kinds of agricultural waste also have higher heating values, which are only slightly lower than those associated with woody biomass. Typical energy content for agricultural waste and woody biomass ranged from 3000 kcal/kg to 4000 kcal/kg as shown in Table 1. Compared with the results of coals, the envirocoal and lignite have lower energy contents due to their higher moisture content (about 13% for envirocoal) and/or ash content (about 45% for lignite). Typical heating values of envirocoal and lignite were approximately 4800 kcal/kg and 2950 kcal/kg, respectively. However, the bituminous, subbituminous and anthracite coals used in this research have higher energy content associated with lower moisture content. Accordingly, the lower heating values of bituminous, subbituminous and anthracite coal ranged approximately from 5600 to 6800 kcal/kg. Consequently, the heating value of waste-refuse-derived fuel is similar with that of bituminous coal and envirocoal, except for the HP-RDF-5. The heating value of HP-RDF-5 was higher than the all tested biomass, even higher than tested coals. This is because the HP-RDF-5 sample contains a higher combustible material content (approximately 96%) than tested coals resulting in higher energy content. Regarding the heating value of agricultural waste and woody biomass, they were obviously similar with the lignite coal. Based on the results of heating values in various tested biomass samples, the tested biomass remains a significant value as fuel for further energy conversion application. Table 2 indicated the cellulose and lignin content in the tested biomass samples conducted in this study. In Table 2, the holocellulose is composed of cellulose and all of the hemicelluloses. That is, the holocellulose represents the total cellulose. Besides, the weight fraction except for the cellulose and lignin fraction corresponds to the fraction of ethanol-toluene extractive hydrocarbons in the tested biomass. According to the results of woody, grass and agricultural biomass analysis, the holocellulose and acid-insoluble lignin contents of the selected biomass are varied from 58% to 72% and from 18% to 37%, respectively. All of the selected biomass samples contain more holocellulose contents than lignin contents. In addition, the lignin content of the biomass could divide into the acid-soluble and acid-insoluble lignin. The Longan trimmings, rice straw, and rice husks contains the higher acid-insoluble lignin contents of all the samples and Chinese Pennisetum has the lowest acid-insoluble lignin content. Generally speaking, the lignin is harder to decompose than the cellulose due to the part of lignin in the biomass consists of benzene rings [28]. Comparison with the content of volatile matter and fixed carbon in the selected biomass, the higher lignin content of the selected biomass could have lower volatile matter content. These

Table 2
Holocellulose, lignin content, and empirical chemical formula of woody and agricultural biomass.

Biomass group	Chemical formula	Ethanol-toluene extractives (%)	Holocellulose (%)	Lignin (%)	
				Acid-soluble	Acid-insoluble
Woody biomass					
Longan trimmings	$CH_{1.148}N_{0.018}O_{0.602}S_{0.0015}Cl_{0.0005}$	2.60	58.98	1.11	37.31
Sawdust*	$CH_{1.653}N_{0.016}O_{0.630}S_{0.0026}Cl_{0.0004}$	4.24	66.18	0.21	29.37
Willow	$CH_{1.619}N_{0.004}O_{0.652}S_{0.0011}Cl_{0.0005}$	5.54	63.23	0.21	31.02
Grass and agricultural biomass					
Bamboo trimmings	$CH_{1.267}N_{0.015}O_{0.600}S_{0.0017}Cl_{0.0008}$	3.81	69.66	1.29	25.24
Bamboo's chopsticks	$CH_{1.281}N_{0.003}O_{0.761}S_{0.0031}Cl_{0.0009}$	5.74	70.52	0.83	22.91
Rice husks	$CH_{1.654}N_{0.007}O_{0.674}S_{0.0033}Cl_{0.0016}$	3.57	59.53	1.00	35.90
Rice straw*	$CH_{1.880}N_{0.035}O_{0.706}S_{0.0052}Cl_{0.0040}$	2.52	58.85	1.91	36.72
Chinese Pennisetum	$CH_{2.023}N_{0.011}O_{0.724}S_{0.0043}Cl_{0.0017}$	8.75	71.71	1.14	18.40
Mushroom waste	$CH_{1.154}N_{0.023}O_{0.593}S_{0.0037}Cl_{0.0015}$	2.72	61.42	2.92	32.94
Edible grass-stem	$CH_{1.616}N_{0.029}O_{0.699}S_{0.0045}Cl_{0.0016}$	5.31	70.09	2.62	21.98
Banana trimmings	$CH_{1.497}N_{0.019}O_{0.620}S_{0.0025}Cl_{0.0010}$	3.51	68.86	1.97	25.66

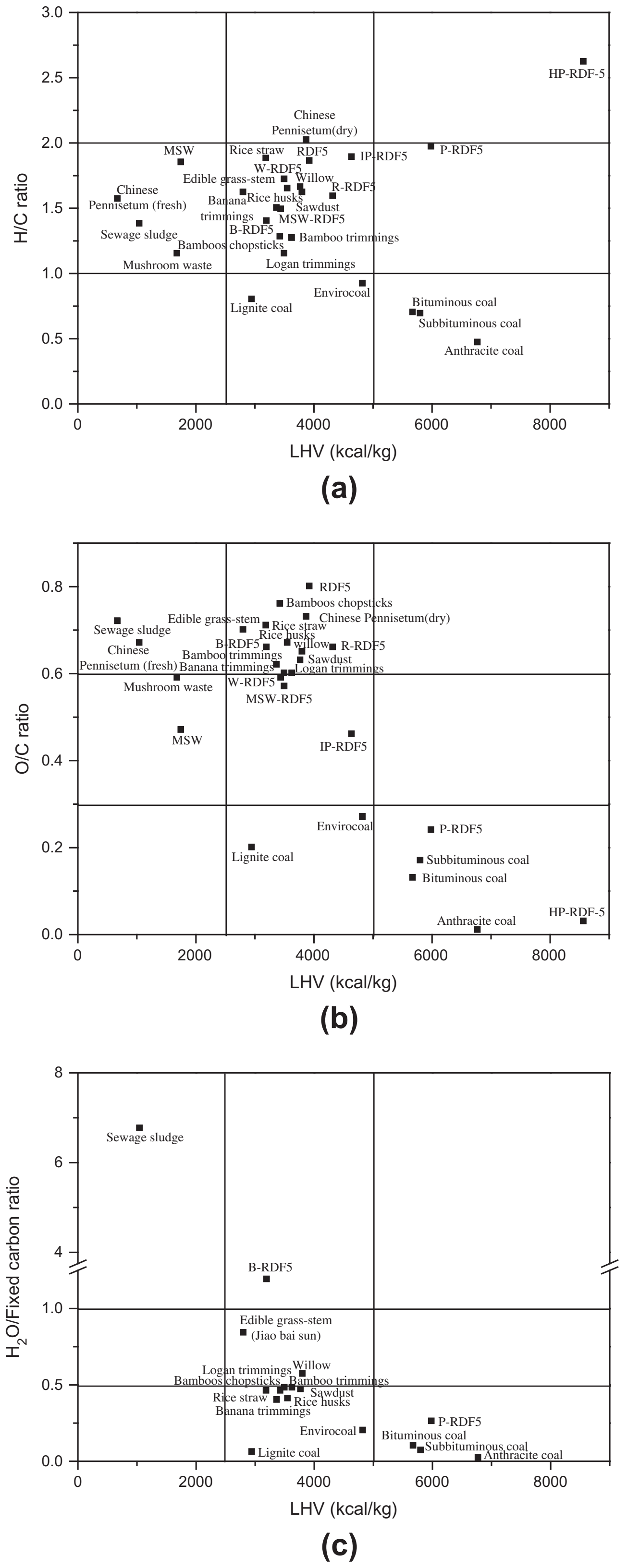

Fig. 3. Relationships between the heating value and mole ratios of elements by cluster analysis.

results can confirm that the volatilization behavior of selected biomass depends on its own component such as the cellulose and lignin content.

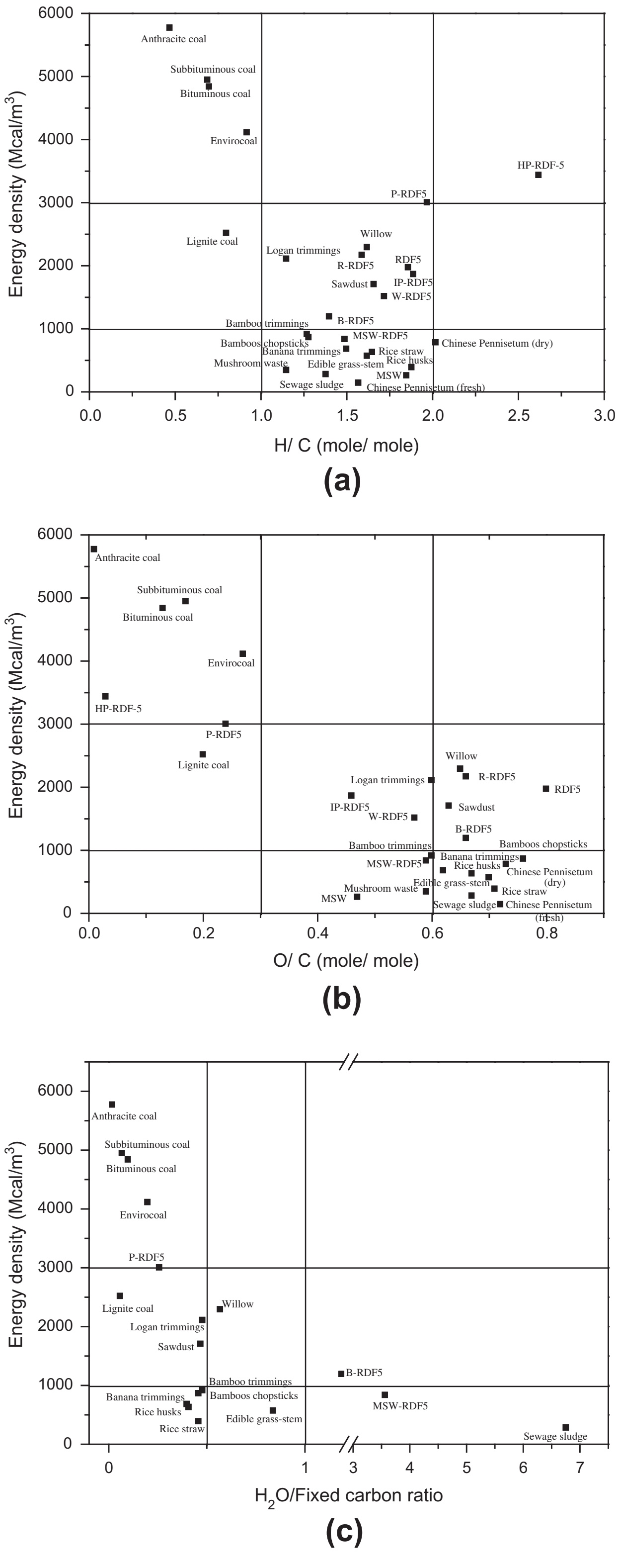

Fig. 4. Relationship between the energy density and mole ratios of elements by cluster analysis.

3.4. Characteristics of biomass energy yield by cluster analysis

In general, the heating value of both biomass and coal increased with an increase in the carbon content of biomass. However, the increase in the hydrogen and oxygen content of the tested biomass would decrease the heating value because the chemical bond

Table 3
Suggestions for pretreatment technologies in thermal conversion process.

Biomass group	Pretreatment techniques			
	Drying	Shredding/size reduction	Briquetting/pelletizing	Torrefied
Woody biomass				
Longan trimmings	○	○	○	○
Sawdust	○		○	○
Willow	○	○	○	○
Grass and agricultural biomass				
Bamboo trimmings		○		○
Bamboo's chopsticks		○		○
Rice husks				○
Rice straw		○		○
Chinese Pennisetum (dry)		○		○
Chinese Pennisetum (fresh)	○	○		○
Mushroom waste	○	○		○
Edible grass-stem (Jiao bai sun)		○		○
Banana trimmings		○		○
Industrial biomass wastes				
Sewage sludge	○		○	○
MSW	○	○	○	
MSW-RDF-5	○		○	
BDF-5			○	
RDF-5			○	
P-RDF-5			○	
HP-RDF-5			○	
IP-RDF-5			○	
R-RDF-5			○	
W-RDF-5			○	

energy of carbon–oxygen and carbon–hydrogen are lower than that of the energy of carbon–carbon bonds. To understand the relationship between the reactivity and heating value of the tested biomass, the hydrogen–carbon molar ratio (referred as H/C ratio) and oxygen–carbon molar ratio (referred as O/C ratio) were used in this research as the reactivity indexes (as shown in Figs. 3 and 4). Based on the results of reactivity by cluster analysis, the woody biomass and most of the agricultural wastes can be classified into groups of medium H/C ratio and high O/C ratio. That is, the above various biomass samples can be identified as having higher reactive characteristics during the thermal conversion process. However, their energy contents only have a medium value ranging between 2500 kcal/kg and 5000 kcal/kg (as shown in Figs. 3 and 4). In addition, the sludge produced from the wastewater treatment plant, municipal solid waste, and mushroom waste can also be classified into a group of medium H/C ratio and high O/C ratio. But their energy contents were less than 2500 kcal/kg. The results, when compared with coal, indicated that the bituminous, subbituminous, and anthracite coals have a lower H/C and O/C ratio (less than 1) and higher energy content (greater than 5000 kcal/kg), respectively. Although the lignite and envirocoal have similarly reactive characteristics of lower H/C and O/C ratio, the energy contents were relatively lower than that of other tested coals. Meanwhile, the lignite and envirocoal also have lower reactivity than that of tested biomass samples. The data on the characteristics of the tested biomass by cluster analysis helps to provide important information for the selection of technologies in the thermal conversion of specific biomass and/or blending of various biomasses.

To further understand the tendency of the water gas reaction ($C + H_2O \rightarrow CO + H_2$) in biomass gasification, the molar ratio of moisture and fixed carbon content (referred as H_2O/FC ratio) was used as an index in this research for assessment of the reaction that occurred in gasification. Fig. 5 showed that woody biomass samples (such as sawdust, willow and longan trimmings) and agricultural wastes (such as edible grass-stem and rice straw) can be classified as a group of medium H_2O/FC ratio (ranged between 0.5 and 1.0) with a heating value ranging between 2500 kcal/kg and 5000 kcal/kg. However, the tested coals (such as bituminous, subbituminous, anthracite) were classified as a group of low H_2O/FC ratio (less than 0.5) and high heating value (greater than 5000 kcal/kg). In general, the tested biomass with a higher H_2O/FC ratio would enhance the energy yield in thermal conversion due to the progression of the water–gas reaction. Therefore, woody biomass and agricultural wastes could easily produce the synthesis gas in gasification due to the biomass having a relatively high moisture content. This is because coal with relatively low H_2O/FC needs to improve synthetic gas production and energy utilization efficiency by the steam reforming reaction in coal gasification.

3.5. Suggestions for pretreatment technologies in thermal conversion of various biomasses

To understand the feasibility of biomass as an energy source, in this research, we attempted to use energy density (ED) as an index for assessing the feasibility of pretreatment techniques of various biomass selections prior to the subsequent specific thermal conversion process. Energy density is defined as the energy content stored in a biomass per unit volume (Mcal/m^3). The energy density of all tested biomass samples were indicated in Table 1. Typical energy density for woody biomass (ranging between 1700 Mcal/m^3 and 2300 Mcal/m^3) was significantly higher than that of herbaceous and agricultural waste (ranging between 136 Mcal/m^3 and 908 Mcal/m^3). Therefore, the herbaceous and agricultural waste in most cases has to be pretreated (drying, shredding, briquetting, or torrefying, etc.) before being used in the thermal conversion process (as shown in Table 2). The energy density of waste-derived fuel was relatively high and ranged from 1186 Mcal/m^3 to 3430 Mcal/m^3 except for sewage sludge and MSW. This is because the waste-derived fuel produced from various wastes reduced its volume by compaction. In summary, the criteria for the selection for pretreatment techniques in the application of biomass thermal conversion was significantly influenced by the moisture content, specific weight, and heating value of biomass. Therefore, to use a suitable pretreatment technique or combined pretreatment methods that could effectively enhance the energy density of biomass and efficiency of energy utilization Table 3.

4. Conclusions

Based on the characteristics results of 26 varieties of biomass produced from forestry, agriculture, municipality, and industry in Taiwan, the following conclusions could be drawn:

(1) Based on the proximate analysis results, the volatile matter and fixed carbon content of tested various biomass samples ranged from 60% to 80% and from 10% to 20%, respectively. Due to the characteristics of higher volatile matter content in the tested biomass, it could have a low ignition temperature resulting in larger amounts of combustible gas production by the thermal conversion technique. In addition, the agricultural wastes have higher ash content that can easily cause agglomeration and erosion during the thermal conversion process.

(2) The tested biomass samples generally exhibited characteristics of higher volatility and energy yield during the thermal conversion process due to the higher H/C and/or O/C ratios in all the tested biomass. The ratio of H_2O/FC is an important factor that affects the performance of thermal conversion (e.g. gasification) technology. The tested biomass with a higher H_2O/FC ratio could enhance energy yield during the thermal conversion process. This is because the progression of the water–gas and water–gas-shift reaction will occurred in the thermal conversion process.

(3) The waste-derived fuel samples, such as fuels derived from plastics, rubber, and wood, could generally have higher sulfur or chlorine content. The trace pollutants emission should be taken into consideration during the thermal conversion process. In conclusion, applying the proper pretreatment technique, such as drying, shredding, briquetting, torrefying, or combined methods, can improve the energy yield efficiency and diversify the energy utilization pathways.

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